...ATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE February 1992	3. REPORT TYPE AND DATES COVERED Professional Paper

4. TITLE AND SUBTITLE

REMOTE SENSING OF AEROSOL EXTINCTION USING SINGLE-ENDED LIDARS

5. FUNDING NUMBERS

PR: SXB3
PE: 0602435N
WU: DN888715

6. AUTHOR(S)

J. H. Richter, H. G. Hughes and M. R. Paulson

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Naval Command, Control and Ocean Surveillance Center (NCCOSC),
Research, Development, Test and Evaluation Division (NRaD)
San Diego, CA 92152–5000

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Naval Ocean Systems Center
Block Programs (now NCCOSC/NRaD)
San Diego, CA 92152–5000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Aerosol extinction is one of the primary factors limiting the performance of systems which rely on visible or infrared radiation in the atmosphere. Lidars have been used to measure the backscattered radiation from aerosols in an attempt to determine extinction. However, techniques for inverting the power returned to a single-ended lidar to obtain range-dependent extinction coefficients requires a knowledge of the relationship between the backscatter and extinction coefficients along the path. If the aerosol distribution in the atmosphere is horizontally homogeneous, the need for knowing the relationship between backscatter and extinction can be eliminated by comparing the powers received from each altitude along two or more different elevation angles, and the extinction coefficient variation in the vertical direction can be determined.

Published in *National Radio Science,* January 1992.

14. SUBJECT TERMS electromagnetic electro-optics propagation	atmosphere	15. NUMBER OF PAGES 16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAME AS REPORT

UNCLASSIFIED

21a. NAME OF RESPONSIBLE INDIVIDUAL	21b. TELEPHONE (Include Area Code)	21c. OFFICE SYMBOL
J. H. Richter	(619) 553-3053	Code 54

92 4 17 088

92-09876

NSN 7540-01-280-5500

Standard form 298

UNCLASSIFIED

F3-5
1000

REMOTE SENSING OF AEROSOL EXTINCTION USING SINGLE-ENDED LIDARS

J.H. Richter, H.G. Hughes and M.R. Paulson
Ocean and Atmospheric Sciences Division, Code 54
Naval Ocean Systems Center
San Diego, CA 92152-5000

Aerosol extinction is one of the primary factors limiting the performance of systems which rely on visible or infrared radiation in the atmosphere. Lidars have been used to measure the backscattered radiation from aerosols in an attempt to determine extinction. However, techniques for inverting the power returned to a single-ended lidar to obtain range-dependent extinction coefficients requires a knowledge of the relationship between the backscatter and extinction coefficients along the path. If the aerosol distribution in the atmosphere is horizontally homogeneous, the need for knowing the relationship between backscatter and extinction can be eliminated by comparing the powers received from each altitude along two or more different elevation angles, and the extinction coefficient variation in the vertical direction can be determined.

A review is presented of past efforts to determine atmospheric extinction from single-ended lidar measurements and the assumptions made concerning backscatter/extinction relationships. The degree to which aerosols within the convectively mixed atmosphere can be expected to be horizontally homogeneous is also discussed. The conclusion is, that the accuracy of extinction coefficients determined by a single-ended lidar cannot be assured unless the extinction/backscatter relationship is known or the atmosphere is horizontally homogeneous over the propagation path.

REMOTE SENSING OF AEROSOL EXTINCTION USING SINGLE-ENDED LIDARS

J. H. Richter, H. G. Hughes and M. R. Paulson

Ocean and Atmospheric Sciences Division
Naval Ocean Systems Center
San Diego, California 92152-5000

1. SUMMARY

Aerosol extinction is one of the primary factors limiting the performance of systems which rely on visible or infrared radiation in the atmosphere. Lidar (light detection and ranging) systems have been used to measure the radiation backscattered to a receiver by aerosols in an attempt to determine extinction. However,the technique of inverting the power returned to a single-ended lidar to obtain range-dependent extinction coefficients requires a knowledge of the relationship between the volumetric backscatter and extinction coefficients along the path. If the atmosphere can be shown to be horizontally homogeneous, the need for knowing the relationship between backscatter and extinction can be eliminated by comparing the powers received from each altitude along two or more different elevation angles, and the extinction coefficient variation in the vertical direction can be readily determined. In this paper, a review is presented of past efforts to determine atmospheric extinction from single-ended lidar measurements of backscatter, and the assumptions made concerning the backscatter /extinction relationships. The degree to which the aerosols within the convectively mixed atmosphere can be expected to be horizontally homogeneous is also discussed. The conclusions are that unless the extinction/backscatter relationship is known, or that the atmosphere is horizontally homogeneous over the propagation path, the accuracies of extinction coefficients determined by a single-ended lidar cannot be assured.

2. INTRODUCTION

The utility of a monostatic lidar system as a remote sensor for obtaining temporal and spatial information about the dynamic processes of the atmosphere is well established. By measuring the power backscattered from a laser pulse at a given range tc a receiver, the movement and relative concentrations naturally occurring aerosols, of industrial pollutants or battlefield obscurants can be monitored, and the bases of clouds determined. Remote mapping of wind velocities and flow patterns over large portions of the atmosphere can also be carried out. In these applications, the lidar is used as a tracer of aerosols which scatter the incident radiation rather than a probe for studying the aerosols' optical properties. There is an extensive amount of literature published on the merits and performance of aerosol tracer lidar techniques (which need not be repeated here). Other lidar systems (Differential Absorption or DIAL and Raman) which utilize a wavelength dependence or frequency-shifted re-radiation of absorption spectra in the atmosphere have been used to obtain vertical profiles of concentrations of various gases.

The use of visible and infrared electro-optical systems for and weapons and sensor systems require the capability to predict how radiation interacts with atmospheric aerosols in the marine environment. For a given aerosol size distribution, extinction can be determined from Mie theory assuming that they scatter and absorb radiation as if they were spheres of known refractive indices. For example, in the well-mixed marine boundary layer, relative humidities are usually high enough that most of the aerosols are hydrated, taking on a spherical shape. But above the layer, where relative humidities are lower, aerosols may be non-spherical. In such cases, the optical properties predicted for spheres may differ by as much as an order of magnitude form those observed. Estimates of slant-path visibilities are required as inputs to computer codes for *scaling selected aerosol* size distribution models with altitude to predict the performance of electrooptical systems. Lidars have been used to determine aerosol extinction. However, the technique of inverting the power returned to a single-ended lidar to obtain range-dependent aerosol extinction coefficients have not yet resulted in techniques or instruments with assured accuracy. In this paper, past efforts to use lidar to measure aerosol extinction are briefly reviewed, and the difficulties are pointed out which need to be overcome before lidars can become operationally useful probes for aerosol extinction.

3. SOLUTIONS TO THE LIDAR EQUATION

The single-scatter lidar equation is given by the relation

$$S(r)=\ln[P(r)r^2]=\ln K+\ln\beta(r)-2\int_0^r(r')dr' \quad (1)$$

In this equation P(r) is the power received from a scattering volume at range r, K is the instrumentation constant, and $\beta(r)$ and $\sigma(r)$ are the volumetric backscatter and extinction coefficients, respectively. In differential form this equation is

$$\frac{dS(r)}{dr}=\frac{1}{\beta(r)}\frac{d\beta(r)}{dr}-2\sigma(r) \quad (2)$$

The solution of equation (2) requires knowing or assuming a relationship between $\beta(r)$ and $\sigma(r)$. However, if the atmosphere is homogeneous, the extinction coefficient can be simply expressed in terms of the rate of change of signal with range, i.e., $\sigma = -1/2 [dS(r)/dr]$. A plot of S(r) vs. r would then yield a straight line whose slope is -2σ.

Various authors (Refs 1 & 2) have presented solutions to equation (2) by assuming a functional relationship between backscatter and extinction to be of the form

$$\beta(r) = C\sigma(r)^{k} \tag{3}$$

where C and k are not dependent upon r. In this case, only the aerosol number density is allowed to vary with range and not the size distribution. When the integration is performed in the forward direction from a range r_o, where the transmitted beam and receiver field-of-view overlap, to a final range r, the extinction coefficient is given by

$$\sigma(r) = \frac{\exp[S(r)]}{\frac{\exp[S(r_o)]}{\sigma(r_o)} - 2\int_{r_o}^{r}\exp[S(r')]dr'} \tag{4}$$

where $\sigma(r_o)$ is the unknown contribution to extinction out to the overlap range.

The instabilities encountered in equation (4) can be overcome by performing the integration in the reverse direction from a final range, r_f, in toward the transmitter. In this case the extinction coefficient is given by,

$$\sigma(r) = \frac{\exp[S(r)]}{\frac{\exp[S(r_f)]}{\sigma(r_f)} + 2\int_{r}^{r_f}\exp[S(r')]dr'} \tag{5}$$

where $\sigma(r_f)$ is the unknown value of extinction at the final range. Solutions to the single-scatter lidar equation have been presented for the reverse and forward integration cases (Ref 3) where the relationship between the backscatter and extinction coefficients is assumed to vary with range according to

$$\beta(r) = C(r)\sigma(r)^{k} \tag{6}$$

where k is a constant. For the forward integration case the extinction coefficient as a function of range is given by

$$\sigma(r) = \frac{\frac{1}{C(r)}\exp[S(r)]}{\frac{\exp[S(r_o)]}{C(r_o)\sigma(r_o)} - 2\int_{r_o}^{r}\frac{1}{C(r')}\exp[S(r')]dr'} \tag{7}$$

and for reverse integration by

$$\sigma(r) = \frac{\frac{1}{C(r)}\exp[S(r)]}{\frac{\exp[S(r_f)]}{C(r_f)\sigma(r_f)} + 2\int_{r}^{r_f}\frac{1}{C(r')}\exp[S(r')]dr'} \tag{8}$$

where the constant k has been chosen to be unity.

4. DISCUSSION

Klett (Ref 1) discussed the instabilities inherent in equation (4) due to the negative sign in the denominator and the uncertainties in the boundary value $\sigma(r_o)$. In order to determine the appropriate value of $\sigma(r_o)$ from the raw lidar return, the values of C and k appropriate for the existing air mass must be known. While the value of k is usually close to unity, a critical problem is determining the proper choice of C. From the work of Barteneva (Ref 4), a change greater than an order of magnitude can be inferred in the value of C between clear air and fog conditions. Kunz (Ref 5) proposed that, for situations where the lower levels of the atmosphere appeared horizontally homogeneous, $\sigma(r_o)$ could be determined from the return of a horizontal lidar shot by means of the slope method, and then used as the boundary value in equation (4) for calculating the extinction in the vertical direction. This approach necessarily assumes that the ratio β/σ remains constant with altitude, and that the linear decrease of return signal with range is indeed indicative a homogeneous atmosphere. Caution must be applied in interpreting linear decreases of S(r) with range as being related to homogeneous conditions. Kunz (Ref 6) has reported examples of vertical lidar returns beneath clouds which seemingly originated from a homogeneous atmosphere without a reflection from cloud base. In conditions where the aerosol size distribution is increasing with range, an increase in backscattered power can be balanced the decrease in power caused by attenuation.

While equation (2) is "stable", it is difficult to use in a practical sense unless there is another independent determination of $\sigma(r_f)$. For fog conditions, the first term in the denominator of equation (5) becomes negligible, but in these situations the single scatter lidar equation is not applicable. Carnuth and Reiter (Ref 7) used an approach to invert lidar returns beneath stratocumulus clouds by assuming $\sigma(r_f)$ to be equal to accepted values of cloud base extinction coefficient ($10\ km^{-1} \le \sigma\text{-}(r_f) \le 30\ km^{-1}$). This approach is still assumes that β/σ is invariant with altitude. Lindberg, et al., (Ref 8) have also presented measurements beneath stratus clouds in Europe. Extinction coefficients determined by the reverse integration technique agreed reasonably well with those calculated from balloon borne particle measurements and point measurements of visibility when the atmosphere was horizontally homogeneous and stable. The method by which $\sigma(r_f)$ was chosen is not clear since the authors only stated that an iteration procedure was used. Ferguson and Stephens (Ref 9) also used an iterative scheme in an attempt to select the value of

$\sigma(r_f)$. The value of $\sigma(r_f)$ at a close-in range (where the returned signal is well above the system noise) was varied until the $\sigma(r)$ determined from equation (5) allowed calculated and measured values of S(r) to agree. The chosen value of $\sigma(r_f)$ was then used as $\sigma(r_o)$ in equation (1) to integrate out from the transmitter. This procedure requires the system to be accurately calibrated and the value of β/σ to be specified and invariant with range. Hughes et al. (Ref 10) showed the extinction coefficients calculated with this algorithm were not unique and were extremely sensitive to the chosen value of β/σ. Bissonnette (Ref 3) pointed out that unless the system calibrations and β/σ are accurately known, this algorithm is no more stable than the forward integration solution.

Carnuth (Ref 11) has attempted to verify the reverse integration technique (Klett's method) by making measurements of the visual range using an integrating nephelometer to obtain $\sigma(r_f)$ at the end of a slanted lidar path (7 km) up the side of a mountain. Optical depths derived from a transmissometer operated simultaneously with the lidar were in agreement with those derived from the averages of several lidar returns in cases where the path appeared homogeneous. In other cases, discrepancies were observed which the authors attributed to the variable ratio of β/σ along the path (in addition to measurement errors and the neglect of multiple scattering effects). Salemink et al. (Ref 12) determined values of σ and β from horizontal lidar shots using the slope method when the atmosphere appeared to be horizontally homogeneous. They then presented a parameterization between values of β/σ and relative humidity (33% $\leq$ RH $\leq$ 87%). When the parameterization was used to invert visible wavelength lidar returns in the vertical direction, the derived extinction coefficient profiles (using radiosonde measurements of relative humidity) sometimes agreed reasonably well with those measured by aircraft mounted extinction meters. In contrast, de Leeuw et al. (Ref 13) using similar types of lidar measurements did not observe a distinct statistical relationship between backscatter and extinction ratios and relative humidity. Fitzgerald (Ref 14) pointed out that other factors such as the aerosol properties can strongly affect the relationship between β/σ and relative humidity and that the power law relationship is not necessarily valid for relative humidities less than about 80%. A unique relationship between C(r) and relative humidity which is dependent on the air mass characteristics is yet to be developed.

An assumed relationship between the backscatter and extinction coefficients can be eliminated by comparing the powers returned from a volume common to each of the two lidars located at opposite ends of the propagation path. For this double-ended lidar configuration, the range-dependent extinction coefficient can be shown (Refs 15 & 16) to be related to the slope of the difference in the range compensated powers measured by the two lidars (1 and 2) at the common range r by the equation

$$\sigma(r) = -\frac{1d}{4dr}[S(r)_1 - S(r)_2] \qquad (9)$$

However, the receiver gain of both lidars must be accurately known since they affect the slope characteristics of the individual S(r) curves. Although the double-ended technique has a practical limitation for tactical situations, e.g., in slant path measurements at sea, it is feasible to use it in aerosol studies and to evaluate the various single-ended schemes for measuring extinction. Hughes and Paulson (Ref 15) used the double-ended lidar configuration over a 1 km inhomogeneous slant path to demonstrate that if the value of C(r) varies with range, but is assumed to be a constant, neither the single-ended forward or reverse integration algorithms will allow range-dependent extinction coefficients to be determined with any assured degree of accuracy even if the initial boundary values are specified. If, however, the manner in which C(r) varies is specified, both the forward and reverse single-ended inversions reproduce the double-ended measurements remarkably well.

In situations where the different layers of the atmosphere are horizontally homogeneous, the need for knowing the relationship between the backscatter and extinction coefficients can be eliminated by comparing the range compensated powers received from each altitude along two or more different elevation angles (Refs 17 & 18). Assuming extinction and backscatter coefficients to vary only in the vertical direction, the optical depth, τ, between any two altitudes can be shown to be

$$\tau = \frac{[S(R_3)-S(R_4)]-[S(R_1)-S(R_2)]}{2(1/\sin\phi_2-1/\sin\phi_1)} \qquad (10)$$

where $S(R_1)$ and $S(R_2)$ are the range compensated powers returned along slant ranges R_1 and R_2 from an altitude h_1 with the lidar elevated at angles ϕ_1 and ϕ_2, respectively, with $\phi_1 < \phi_2$. Similarly, $S(R_3)$ and $S(R_4)$ refer to the range compensated powers returned from an altitude h_2 with the lidar elevated at an angle ϕ_2 where $\phi_2 < \phi_1$. In principle, if the atmosphere were horizontally homogeneous, the lidar beam could be swept in elevation and the method used between closely separated angles to obtain an incremented profile of extinction and backscatter (Ref 19). The smaller angular separations, however, place stringent requirements on the accuracies to which the range compensated powers must be measured (Ref 18). Also,the works of Russell and Livingston (Ref 17), and Spinhirne et al. (Ref 20) concluded that the atmosphere within the convectively mixed marine boundary layer rarely, if ever, has the degree of homogeneity required. Atlas et al. (Ref 21) presented examples of lidar returns observed from an aircraft above the marine boundary layer. The returns from within the mixed layer were shown to be associated with updrafts carrying aerosol-rich air upward and conversely. These effects were enhanced by increasing humidity updrafts and decreas-

ing humidity downwards that operate to increase and decrease aerosol sizes within small scale sizes between 200 and 500 meters superimposed upon the large scale (1-2 km) undulations of the inversion.

It has been demonstrated by Paulson (Ref 18) that the double angle technique can be used to determine the extent to which the atmosphere is horizontally homogeneous. In these studies, data were taken beneath a thin stratus cloud layer at about 500 meters. Two calibrated Visioceilometer lidars (Ref 8) were operated side-by-side on the west side of the Point Loma Peninsula at San Diego, Calif. and pointed west over the Pacific Ocean. A series of nearly simultaneous shots were made with the one lidar elevated at an angle of 25° and the other at 50°. S(r) values for each of the lidars (determined using 5-point running averages of the raw data) showed increasing returns with increasing range and fluctuated about one another at different ranges which indicated an *inhomogeneous condition*. The optical depths between different altitudes determined from Equation 10 are shown in the following table:

TABLE 1. Optical depths calculated from different altitudes up to a maximum altitude of 475 meters on 17 May 1989.

Lower Altitude (meters)	Optical depth
100	0.811
125	0.437
150	0.584
175	0.597
200	0.647
225	0.584
250	0.688
275	0.150
300	0.260
325	0.260
350	0.342
375	0.492

The optical depth between 275 and 475 meters is only 0.15, while that from 375 to 475 meters is more that three times greater (0.49). If the data were representative of a horizontally homogeneous condition, the optical depth up to 475 meters should consistently decrease as h_l increases. These data demonstrate that, even though the magnitude of S(r) from a horizontal lidar return decreases linearly with range, horizontal homogeneity can only be assured if optical depths within the boundary layer measured by the two-angle method decrease as contributions from the close-in returns are eliminated.

5. CONCLUSIONS

Range-dependent extinction coefficients cannot be determined from single-ended lidar measurements with any assured degree of accuracy unless the backscatter/extinction coefficient ratio is known along the propagation path or the atmosphere is horizontally homogeneous. If the conditions exist for which the forward inversion algorithm is stable, the double-ended lidar work has shown that a single-ended lidar inversion technique would be possible when augmented with a close-in measurement of extinction and measurements to relate C(r) to air mass characteristics and relative humidity. While the works of Mulders (Ref 22) and de Leeuw et al. (Ref 13) have concluded no relationship exists between C(r) and relative humidity, their measurements did not account for changes in the air mass characteristics. Simultaneous lidar measurements and air mass characteristics (e.g., radon and condensation nuclei) need to be conducted to identify their relationship to relative humidity profiles. Whether or not such a relationship can ever be identified in a practical sense is yet to be determined.

For a single-ended lidar to become a useful operational tool, innovative concepts need to be pursued. A novel single-ended lidar technique has been recently proposed by Hooper and Gerber (Refs 23 & 24) to measure optical depths when used down-looking from an aircraft or satellite at the ocean surface and when the reflection properties of the surface are known. In this technique, two detectors are used: one with a narrow field-of-view, which measures the power *directly reflected off the rough ocean* surface and another with a wide field-of-view where the directly reflected photons are blocked (aureole detector). The accuracy of the system is presently being evaluated by comparing the optical depths inferred from the direct and aureole scattered returns to those calculated from size distributions measured simultaneously from an aircraft. Should the aureole system be proven reliable it would be most useful if the optical depths determined using visible or near infrared wavelengths could be scaled directly to the mid or far infrared wavelength bands at which many important EO systems operate.

6. ACKNOWLEDGEMENT

This work was supported by the Office of Naval Technology.

7. REFERENCES

1. Klett, J.D., "Stable Analytical Inversion Solution for Processing Lidar Returns," Appl. Opt., 20, 211 (1981).

2. Kohl, R.H., "Discussion of the Interpretation Problem Encountered in Single-Wavelength Lidar Transmissometers," J. Appl. Meteorol., 17, 1034 (1978).

3. Bissonnette, L.R., "Sensitivity Analysis of Lidar Inversion Algorithms," Appl. Opt., 25, 2122 (1986).

4. Barteneva, O.D., "Scattering Functions of Light in the Atmospheric Boundary Layer," Bull. Acad. Sci. USSR Geophys., Ser. 12, 32 (1960).

5. Kunz, G.J., "Vertical Atmospheric Profiles Measured with Lidar," Appl. Opt., 22, 1955 (1983).

6. Kunz, G.J., "Lidar and Missing Clouds," Appl. Opt., 26, 1161 (1987).

7. Carnuth, W., and R. Reiter, "Cloud Extinction Profile Measurements by Lidar Using Klett's Inversion Method," Appl. Opt., 25, 2899 (1986).

8. Lindberg, J.D., W. J. Lentz, E. M. Measure, and R. Rubio, "Lidar Determinations of Extinction in Stratus Clouds," Appl. Opt., 23, 2172 (1984).

9. Ferguson, J. A., and D. H. Stephens, "Algorithm for Inverting Lidar Returns," Appl. Opt., 22, 3673 (1983).

10. Hughes, H. G, J. A. Ferguson, and D. H. Stephens, "Sensitivity of a Lidar Inversion Algorithm to Parameters Relating Atmospheric Backscatter and Extinction," Appl. Opt., 24, 1609 (1985).

11. Carnuth, W., "Verification of Klett's Method by Comparison of Lidar and Transmissometer Measurements," AGARD Conference Proceedings No. 454, Paper No. 30, 1989.

12. Salemink, H.W.M., P. Schotanus, and J.B. Bergwerff, "Quantitative Lidar at 532 nm for Vertical Extinction Profiles and the Effect of Relative Humidity," Appl. Phys., B34, 187 (1984).

13. de Leeuw, G., G. J. Kunz, and C. W. Lamberts, "Humidity Effects on the Backscatter/Extinction Ratio," Appl. Opt., 25, 3971 (1986).

14. Fitzgerald, J. W., "Effect of Relative Humidity on the Aerosol Backscattering Coefficient at .694 and 10.6 µm Wavelengths," Appl. Opt., 23, 411 (1984).

15. Hughes, H. G., and M. R. Paulson, "Double-Ended Lidar Technique for Aerosol Studies," Appl. Opt., 27, 2273 (1988).

16. Kunz, G. J., "Bipath Method as a Way to Measure the Spatial Backscatter and Extinction Coefficients with Lidar," Appl. Opt., 26, 794 (1987).

17. Russell, P. B., and J. M. Livingston, "Slant-Path Extinction Measurements and Their Relation to Measured and Calculated Albedo Changes," J. Clim. and Appl. Meteor. 23, 1204 (1984).

18. Paulson, M. R., Atmospheric Horizontal Inhomogeneity Effects on the Optical Depths Determined by the Double Elevation Angle Lidar Technique," Naval Ocean Systems Center Technical Document 1600 (1989).

19. Kunz, G. J., "A Method for Measuring the Vertical Extinction and Backscatter Profile with a Scanning Lidar," TNO Physics and Electronics Laboratory, Report No. FEL 1988-65 (1988).

20. Spinhirne, J. D., J. A. Ragan and B. M. Herman, "Vertical Distribution of Aerosol Extinction Cross Section and Inference of Aerosol Imaginary Index in the Troposphere by Lidar Technique," J.Appl. Meteor., 19, 426 (1980).

21. Atlas, D., B. Walter, S. Chou and P. J. Sheu, "The Structure of the Unstable Marine Boundary Layer Viewed by Lidar and Aircraft Observations," J. Atmos. Sci., 43, 1301 (1986).

22. Mulders, J. M., "Algorithm for Inverting Lidar Returns: Comment," Appl. Opt., 23, 2855 (1984).

23. Hooper, W.P., and H. Gerber, "Down Looking Lidar Inversion Constrained by Ocean Reflection and Forward Scatter of Laser Light," Appl. Opt., 21, 689 (1986).

24. Hooper, W. P., and H. Gerber, "Monte Carlo Simulations of Laser-Generated Sea Surface Aureole," Appl. Opt., 27, 5111 (1988).